

THIN-FILM BALLISTIC SEMICONDUCTOR WITH ASYMMETRIC CONDUCTANCE

BACKGROUND

[0001] The present invention relates generally to thermoelectric materials, and more particularly to a solid state thermoelectric structure with asymmetric ballistic conductance.

[0002] The ability to control the direction and magnitude of energy flow in one dimension (wire), two dimension (thin film), and three dimension (bulk) solid state components has been considered critical to device performance since the beginning of the electronic age. Directionality of thermal and electrical currents is a critical concern in thermoelectric devices, diodes, and other electronic valves. The dimensionless thermoelectric figure of merit, a measure of thermoelectric performance, is defined as

$$ZT = \frac{S^2 \sigma T}{\kappa}, \quad [\text{Equation 1}]$$

where S, σ , κ and T are the Seebeck coefficient, electrical conductivity, thermal conductivity and absolute temperature respectively. The best bulk thermoelectric materials have $ZT \sim 1.0$ near room temperature, although there have recently been reports of p-type materials having $ZT \sim 1.8$. Materials with $ZT \sim 1.5$ have been demonstrated at higher temperatures. It is generally recognized that materials must exhibit at least $ZT \sim 2$ for thermoelectric devices to be viable for solid-state cooling, and that $ZT \sim 5$ is necessary to significantly impact commercial and military markets.

[0003] Thin film semiconductor and semi-metals show promise for substantial gains in ZT. Power factor ($S^2 \sigma$) in thin films can be increased due to charge confinement in an effectively two-dimensional film, and the resulting quantum mechanical peak in the electron density of states. If σ is increased while κ is decreased, ZT may be further improved. Unfortunately, increases in electrical conductivity σ (which typically arise due to increased dopant concentration) tend to lead to a corresponding increase in thermal conductivity κ , as thermal energy in a semiconductor is carried by both electrons and phonons (i.e., quantized lattice vibrations). According to the Wiedemann-Franz law, the ratio between σ and the electronic contribution to the thermal conductivity, κ_{el} , is

$$\frac{\sigma}{\kappa_{el}} = \frac{1}{LT}, \quad [\text{Equation 2}]$$

where L is the Lorentz number. Because the Lorentz number is constant for most materials, the ratio σ/κ_{el} is generally assumed to be fixed. Fortunately, the electrical conductivity and thermal conductivity appearing in Equation 1 correspond to opposite directions of carrier transport in the thermoelectric material. The relevant direction for the electrical conductivity is the direction in which the applied electric field drives charge (i.e. the forward current direction). The relevant direction for the thermal conductivity is the direction in which the temperature gradient drives charge (i.e. the reverse current direction). Thus, in the limit of zero phonon contribution to thermal transport,

$$ZT = \frac{S^2 \sigma_{forward}}{L \sigma_{reverse}}, \quad [\text{Equation 3}]$$

[0004] Improvements in ZT can be realized if the ratio between forward and reverse electrical conductivities $\sigma_{forward}/\sigma_{reverse}$ is maximized. One method for producing materials with $\sigma_{forward}/\sigma_{reverse} < 1$ by creating a series of asymmetric inclusions to alter current flow was presented in U.S. Patent application US2010/0044644 A1 entitled, "Composite Material with Anisotropic Electrical and Thermal Conductivities," filed Aug. 19, 2008.

SUMMARY

[0005] A thermoelectric structure comprises a thin thermoelectric film extending in a plane between parallel first and second shorting bars. A plurality of curved ballistic scattering guides are formed in a magnetic field region of the thin thermoelectric film subjected to a local, substantially uniform, nonzero magnetic field normal to the plane of the thin thermoelectric film.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. 1 is a schematic view of a thermoelectric structure according to the present invention.

[0007] FIG. 2A is an illustrative trajectory plot of forward charge transport through the thermoelectric structure of FIG. 1.

[0008] FIG. 2B is an illustrative trajectory plot of reverse charge transport through the thermoelectric structure of FIG. 1.

DETAILED DESCRIPTION

[0009] FIG. 1 is a schematic diagram of thermoelectric structure 10. FIG. 1 depicts asymmetric conductance region 12, shorting bars 14 and 16, magnetic field region 18, collimating regions 20 and 22, collimating guides 24, curved guides 26, and magnetic material 28.

[0010] Thermoelectric structure 10 is a substantially two-dimensional thermal diode formed on a thin semiconductor or semi-metal film. Thermoelectric structure 10 may be formed atom layer by atom layer by physical vapor deposition (PVD) methods such as molecular beam epitaxy (MBE), ion beam deposition (IBD), electron beam deposition (EBD), and others known to those skilled in the art. Thermoelectric structure 10 may, for instance, be formed of a high-mobility semiconductor or semi-metal such as graphene, gallium nitride, or silicon carbide, and has a thickness less than the mean free path of an electron in the material. Thermoelectric structure 10 includes at least one asymmetric conductance region 12 defined between shorting bars 14 and 16. Shorting bars 14 and 16 are thin regions of conductive material such as doped graphene or deposited layers of a conductor such as platinum or gold formed in or on thermoelectric structure 10. Shorting bars 14 and 16 act as electrodes, and collect charges passing through asymmetric conductance region 12. Thermoelectric structure 10 may comprise a plurality of repeating asymmetric conductance regions 12 arranged sequentially end-to-end in series, each separated from the next by a shorting bar. Similarly, a plurality of thermoelectric structures 10 can be stacked atop one another with intermediate isolating layers to form a three dimensional composite structure.